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results from the CLASH-project

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WAVE OVERTOPPING AT COASTAL STRUCTURES: RESULTS FROM THE CLASH-PROJECT

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ABSTRACT
The European research project CLASH (EVK3-CT-2001-00058) investigated wave overtopping at coastal structures. More specific it was aimed to develop a generic prediction method for wave overtopping and to solve the problem of suspected scale effects. The present paper summarizes the main results concerning these items.

KEYWORDS

wave overtopping – full scale measurements – model tests – scale effects

1 CLASH – INTRODUCTION
The EU-fifth framework research project CLASH provided the framework for the research required to come up with the results presented in this paper.
The CLASH-team consisted of 13 partners from 7 distinct European countries. They joined mainly due to two observations. The first observation was that actually there was a lack of widely applicable and safe prediction methods for structure design with regard to wave overtopping. Although there exist several overtopping formulae for specific coastal structures, they rely on empirical fitting of equations to overtopping data, which are available from model tests. Moreover, the available overtopping data for different structure types have not been integrated to give a single design method.
A second observation was that prediction methods, based on traditional small scale model data, may be subject to scale or model effects. De Rouck et al. (2001) found that the 2% exceedance level for wave run-up $Ru_{2\%}$ on rubble mound slopes, measured during full scale storms, was about 20% higher than modelled by selected hydraulic laboratories in small scale test facilities. Since wave overtopping is clearly related to wave run up, in fact wave overtopping occurs when the wave run up level exceeds the crest level of the structure, the same effect was suspected for wave overtopping.

The main objectives of the CLASH project were:

- to solve the problem of suspected scale effects for wave overtopping;
- to produce a generic prediction method for wave overtopping and so for crest level design or assessment of coastal structures;

To fullfill these objectives, two main approaches have been used:
The first approach is based on prototype measurements of wave overtopping at selected field sites, laboratory reproduction and numerical modelling. Unique prototype measurements were performed at three locations in Europe: a steep rubble mound breakwater in Zeebrugge (Belgium) (Troch et al., 2004) , a rubble mound breakwater in shallow water in Ostia (Italy) (Briganti et al., 2005) and a vertical wall at Samphire Hoe (UK) (Pullen et al., 2004). The measured events were then simulated in small scale labaroraty model tests. Comparison of model and prototype results has lead to a conclusion on scale effects and how to deal with them.
The second approach is based on the collection of overtopping data available from a lot of model test results at different institutions worldwide into a homogeneous overtopping database. This database

has been supplemented with prototype and laboratory data within the project and was the basis for the development of a generic prediction method based on neural network modelling (see section 2).
To tackle the CLASH objectives, a detailed methodology was established. The work to be performed was structured in 10 distinct but clearly interrelated Workpackages. Fig. 1 shows the interconnection diagram of the project's Workpackages.

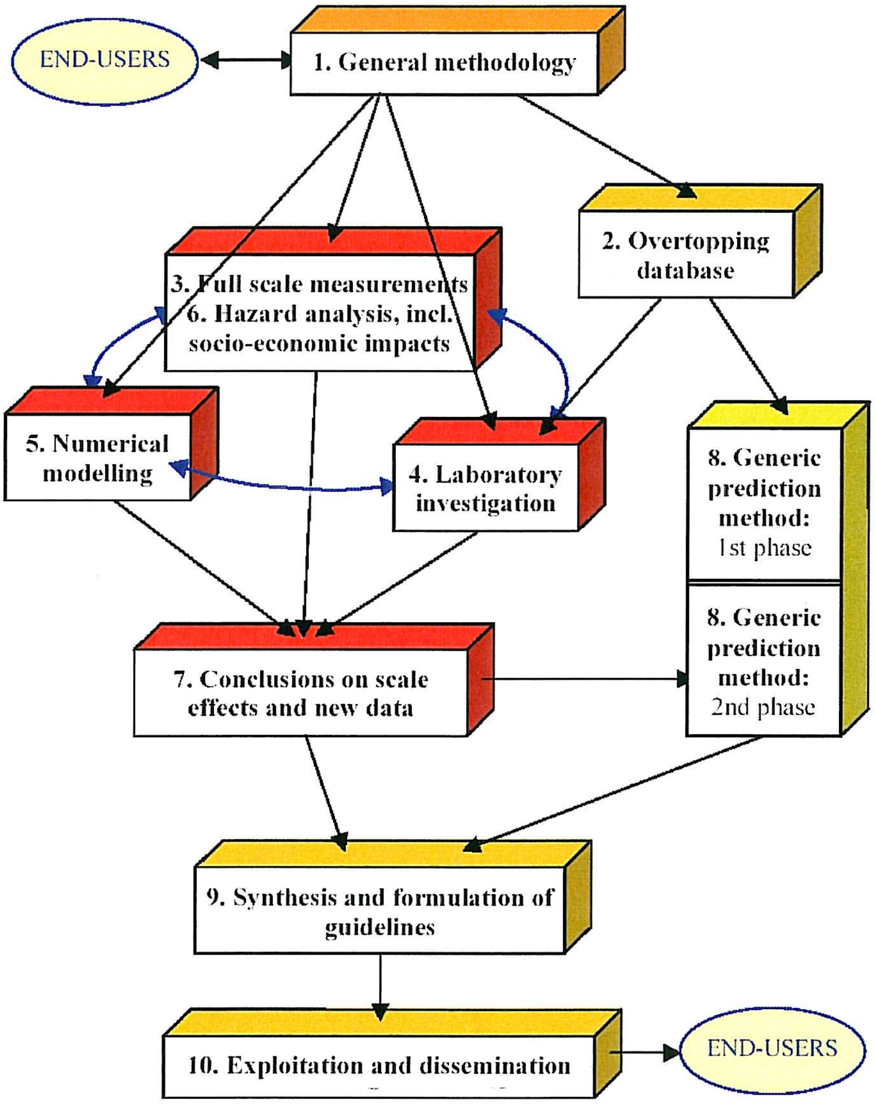

Fig. 1 CLASH interconnection diagram between different Workpackages.

2 GENERIC PREDICTION METHOD

Given the guidance on allowable overtopping discharges for specific hazards from the previous section, the water manager has an idea of the acceptable amount of overtopping. Consequently, the missing link is a prediction of the overtopping amounts to be expected for a given coastal defence and a given seastate. A generic prediction method able to predict wave overtopping for a wide variety of coastal structures has been developed within CLASH. This generic prediction method has been established using the technique of neural network modelling.

2.1 Neural network modelling

Neural networks (NN) are data analyses or modelling techniques commonly used in artificial intelligence. NN are often used as generalised regression techniques for the modelling of cause-effect relations and have proven to be very effective in solving difficult optimization problems in a variety of technical and scientific fields. They are an alternative technique for processes in which the interrelationship of parameters is unclear while sufficient experimental data is available. This technique has been successfully used in the past. Examples of NN modelling on coastal structures are: Mase et al. (1995) for stability of armour breakwaters under wave attack and Van Gent and Van den Boogaard (1998) for wave forces on vertical structures. In the present case, NN are used for prediction of mean wave overtopping discharges and makes use of a much larger data set than in the other NN studies.

NN are organised in the form of layers (Fig. 2) and within each layer there are one or more processing elements called 'neurons'. A standard multi-layer feed-forward NN consists of several units connected in one direction only. The first layer is called the input layer and consists of a number of neurons equal to the number of input parameters. The last layer is called the output layer and consists of a number of neurons equal to the number of output parameters to be predicted. The layers between the input and output layers are called hidden layers and consist of a number of neurons to be defined in the preparation of the NN. Each neuron in each layer receives information from the preceding layer through connectivities. A weight factor is assigned to each connectivity as a result of the training of the NN. The input of a neuron consists of a weighted sum of the outputs of the preceding layer. For the current investigation, the output of a neuron is generated using a non-linear activation function for the hidden layers and a linear activation function for the output layer (Haykin, 1994). This procedure is followed for each neuron. The output neuron generates the final prediction of the NN.

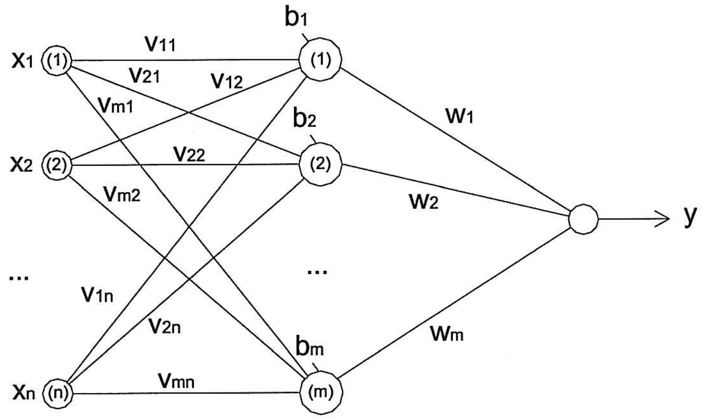

Fig. 2 Schematic representation of a NN.

2.2 Prediction tool

2.2.1 Development of NN based on CLASH – database

The described methodology to develop a NN has been applied to the CLASH homogeneous overtopping database, containing more than 10000 overtopping data and being the largest database on wave overtopping worldwide. For each of these tests a fixed number of parameters was included in this database, summarising the most important information of the test. The main difficulty consisted of choosing adequate parameters to describe the overtopping tests and the cross-sections of the tested structures. Finally, 31 parameters described every test. Besides structural parameters and wave parameters, also some general parameters were assigned to each test: e.g. a factor indicating the reliability of the test and a factor indicating the complexity of the overtopping structure.
It is clear that the database, besides as basis for the NN prediction method, can also be used as a stand-alone tool, since it creates the possibility to extract data, related to specific structures, to validate new analytical or numerical research, ...

The procedure as described in "Neural network modelling" resulted in a generic prediction method for wave overtopping which is suitable for a large variety of coastal structures. The prediction method exists from a piece of software which demands 15 parameters as input. These parameters are both structural and hydraulic parameters. A manual on how to use the prediction tool is attached to the tool itself. This manual also gives clear definitions for all input parameters in order to allow the users to determine the correct values of all input parameters and this way to achieve a prediction which is as accurate as possible. To illustrate this Fig. 3 gives a cross-section of a sloping coastal defence. The input parameters necessary for the NN are indicated in the Figure.

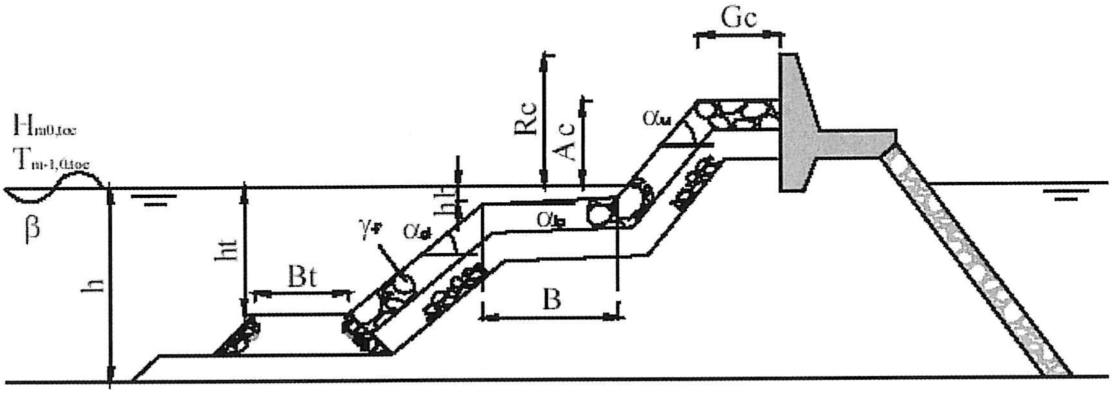

Fig. 3 Cross section of a coastal structure indicating relevant input parameters for NN.

2.2.2. Assumptions and consequences – features of the tool

The prediction tool is based on the CLASH database which means that the range of applicability for each of the input parameters is determined by this database. Since the database covers an enormous amount of overtopping data, this range of applicability is rather wide for most of the parameters. However, to take into account the limits, a clear message is given to the user when a value out of the range of applicability is given for one (or more) of the input parameters. No overtopping prediction is given in this case, to avoid wrong use of the tool.

The NN prediction method actually consists from 500 different NNs, which allows to give a statistical value to the final prediction. The latter is performed by giving a 90% confidence interval together with the prediction. A small confidence interval means that the different NNs all give similar predictions, while a larger interval means that there is q lot of scatter in the prediction by the different NNs. Actually a similar prediction by all NNs means that the specific requested combination of coastal structure – sea state is covered well in the database. Scatter in the NN predictions, resulting in a rather large confidence interval means that the number of available data in the database corresponding to the requested situation is rather limited.

Since the large majority of the data in the database are small scale model data, the NN basically gives a prediction based on these small scale data. However, within the CLASH-project a thorough comparison between measured overtopping during on the one hand prototype storms and on the other hand their laboratory reproductions was performed. This resulted in a procedure which allows to determine the magnitude of the scale and model effects that can be expected when performing small scale model tests. The final prediction tool is equiped with the results of this scaling procedure too. This is manifested by a dual output of the prediction method: on the one hand the prediction based on small scale data is given, while on the other hand a prediction corrected with a possible scale / model factor is provided. The latter has of course the major value for real life applications, while the previous can be used to predict overtopping discharges in small scale models.

Two main application domains for the presented generic prediction method are distinguished. On the one hand the design of new structures to be built, can be made using the generic prediction method.

On the other hand an assessment of the crest level of existing structures can be performed. If necessary, in the latter case the responsible authorities can decide to adapt a coastal structure, to limit the access to the structure, or to adapt the use of the area behind the structure, ...

2.2.3. Practical example

To illustrate how the NN prediction method could be used, together with the guidance on hazards a practical example has been worked out: Starting from a given geometry and sea-state, the influence of the expected sea level rise can be assessed.
Assume a simple smooth dike with following geometric characteristics:

- slope: cotanα = 2.5
- crest width G_c = 3.0 m
- crest freeboard R_c = 2.0 m

The sea state is characterized by:

- significant wave height H_s = 1.50 m
- wave period T = 6.0 s
- water depth d = 5.0 m

To investigate the effect of a suspected sea level rise, the crest freeboard R_c varying between 6m and 0.5 m was given as input value to the prediction tool, while keeping all other parameters constant. Fig. 4 shows a graph where the predicted overtopping discharge is plotted versus the crest freeboard. From the graph it is clear that the predicted overtopping discharge rapidly increases with decreasing crest freeboard.

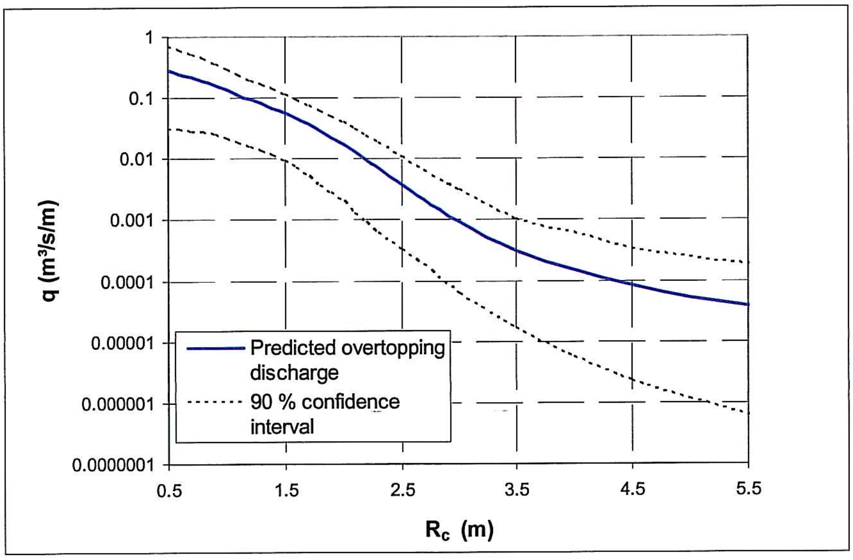

Fig. 4 Output of the NN for the given example. Influence of change in water level (crest freeboard) on the overtopping discharge.

3. Scale effects

3.1. Field Measurements

Field measurements of overtopping have been made on three different types of coastal structures (Fig. 5): a rubble mound breakwater armoured with flattened Antifer cubes at Zeebrugge, Belgium (De Rouck et al., 2003 and Troch et al., 2004), a rock armoured rubble mound breakwater in shallow water at Ostia, Italy (Briganti et al., 2005) and a vertical seawall with rubble mound toe protection at Samphire Hoe, United Kingdom (Pullen et al., 2003).

Fig. 5a Wave overtopping at Samphire Hoe (U.K.)

Fig. 5b Wave overtopping at Zeebrugge (Belgium).

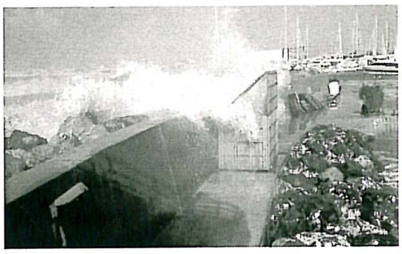

Fig. 5c Wave overtopping at Ostia (Italy).

3.2. Laboratory Reproductions

Wave overtopping has been simulated at small scale for each of the three field sites, with tests in two laboratories for each site. Laboratory tests consisted of two main tasks: (i) reproduction of the measured prototype storms and (ii) parametric tests. Results from different scale models are compared to each other, to prototype results and to prediction formulae from literature.

3.3. Scale factor

A thorough comparison between field data and laboratory data for all three sites has been made. For the sloping rubble mound structures clear differences between model test and prototype results are identified: small overtopping discharges are clearly underestimated in small scale models. Part of the differences can be explained by laboratory effects (Kortenhaus et al. 2004). However, from the present results and a literature review, it can be concluded that for these situations scale effects are present too. This section presents a procedure how to take into account scale / model and wind effects for wave overtopping starting from small scale model test results. Observations in the model and prototype, supported by literature show:

- scale effects have only been observed for sloping structures, not for vertical ones
- the scaling factor is larger for lower overtopping rates
- roughness of the slope must be included
- wind effects should be included
- scale effect is slope dependent

Fig. 6 shows data of both the Ostia and Zeebrugge sites. On the X-axis the overtopping rate from the model, upscaled to prototype scale by means of Froude scaling law is found (q_{SS}). The Y-axis shows the ratio between the overtopping discharge from on the one hand prototype and on the other hand the corresponding model reproduction, again upscaled. This ratio, when different from 1, represents a scaling factor to apply on small scale model overtopping results.

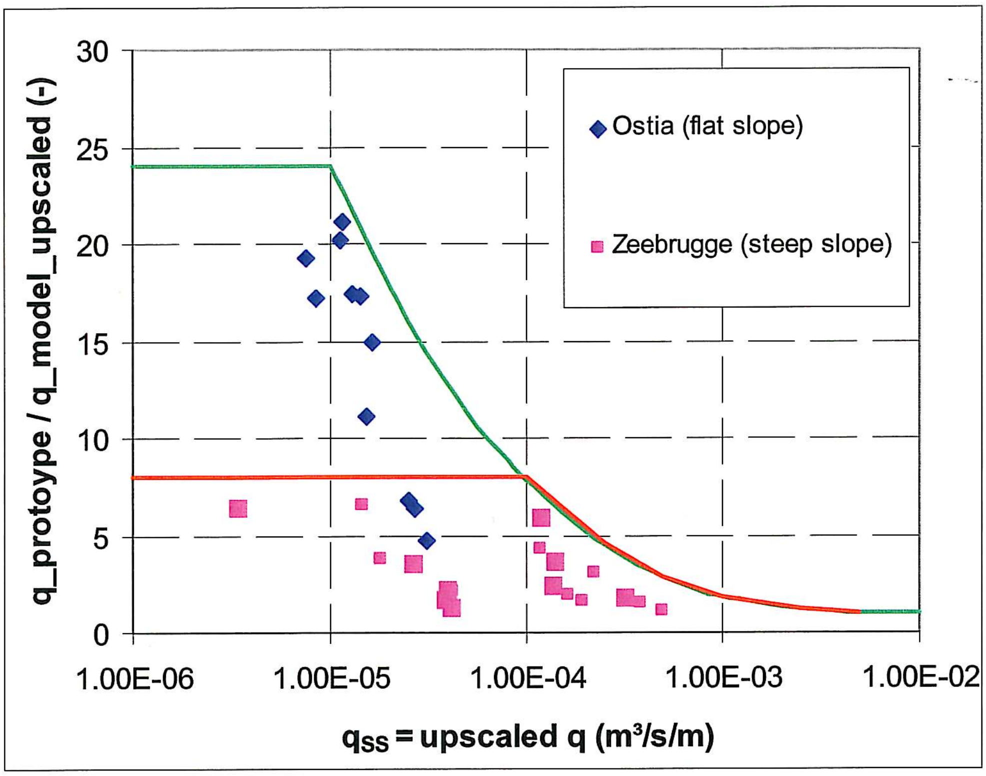

Fig. 6 Scaling factor to apply on small scale model overtopping results as a function of both structure slope and measured overtopping discharge

Fig. 6 indicates that the scaling factor (including model effects, like wind) decreases rather rapidly with increasing value of the overtopping rate. The graph also shows that the scaling factor is smaller for the Zeebrugge breakwater than for the Ostia breakwater. The different structure slope (1/1.4 for Zeebrugge; 1/3.5 for Ostia) is suspected to be the main reason for this difference. These findings have led to a distinction in the scaling procedure (see below) between flat and steep rubble mound breakwater slopes.

Fig. 6 was the basis for the development of a scaling procedure to take into account when using small scale model results on wave overtopping. The procedure itself can be found in De Rouck et al. (2005) and main results are summarized here.

3.3.1.Smooth and vertical structures

Overtopping data with and without wind have been compared to determine the effect of wind on the overtopping rate. The following formula for the factor f_{wind} has been determined:

$$f_{wind} = \begin{cases} 4.0 & \text{for } q_{SS} < 1\cdot 10^{-5}\,\mathrm{m}^3/\mathrm{s}\cdot\mathrm{m} \\ 1.0 + 3\cdot\left(\dfrac{-\log q_{SS} - 2}{3}\right)^3 & \text{for } q_{SS} < 1\cdot 10^{-2}\,\mathrm{m}^3/\mathrm{s}\cdot\mathrm{m} \\ 1.0 & \text{for } q_{SS} \geq 1\cdot 10^{-2}\,\mathrm{m}^3/\mathrm{s}\cdot\mathrm{m} \end{cases} \qquad (1)$$

In which q_{SS} is a small scale model overtopping result or a prediction by the CLASH Neural Network already scaled up to prototype scale by means of Froude scaling law.

In this instance the factor 4.0 is not a scaling factor as previously described, but it can be used to make an allowance for the effects of the wind, and also has the advantage of not using a separate technique. It is especially important to make this distinction, because no scaling effects for vertical and composite vertical structures have been observed. Eq. (1) gives the maximum influence of wind on the overtopping rate for vertical structures or smooth sloping structures.

3.3.2 Rough sloping structures

If the roughness coefficient γ_f is smaller than 0.9 the structure is considered to be a rough sloping structure otherwise the structure is smooth.

The scale factor for flat sloping rubble mound breakwaters (based on slope 1:3.5) including wind effects reads:

$$f_{scale\_wind\_max} = \begin{cases} 24.0 & \text{for } q_{SS} < 1\cdot10^{-5}\ \mathrm{m^3/s\cdot m} \\ 1.0 + 23\cdot\left(\dfrac{-\log q_{SS} - 2}{3}\right)^3 & \text{for } q_{SS} < 1\cdot10^{-2}\ \mathrm{m^3/s\cdot m} \\ 1.0 & \text{for } q_{SS} \geq 1\cdot10^{-2}\ \mathrm{m^3/s\cdot m} \end{cases} \quad (2a)$$

For steep sloping rubble mound breakwaters (based on slope 1:1.4) this becomes:

$$f_{scale\_wind\_max} = \begin{cases} 8.0 & \text{for } q_{ss} < 1.10^{-4}\ \mathrm{m^3/s.m} \\ 1.0 + 7\ .\left(\dfrac{-\log q_{ss} - 2}{2}\right)^3 & \text{for } q_{ss} < 1.10^{-2}\ \mathrm{m^3/s.m} \\ 1.0 & \text{for } q_{ss} \geq 1.10^{-2}\ \mathrm{m^3/s.m} \end{cases} \quad (2b)$$

It should be noted that this factor, as calculated by eq. (2) includes both the influence of scale and wind effects, the latter being a model rather than a scale effect. Furthermore, for scale effects without any wind a maximum value of 16.0 is suggested (flat slopes). Assuming that factors for scale and wind effects should be multiplied to achieve an overall factor, a theoretical factor for wind of 1.5 would be obtained. This is lower than indicated in Eq. (1) for vertical walls, which is believed to be due to the effect of wind for vertical structures being larger than for rough sloping structures. Applying the factor of 1.5 for wind, leads to a maximum effect of 5.33 for scale effects without wind for steep sloping rubble mounds, which is changed to 6.0 for practical reasons. So, for scale effects without wind following equation is suggested:

Flat sloping rubble mound breakwaters (based on slope 1:3.5):

$$f_{scale\_nw} = \begin{cases} 16.0 & \text{for } q_{SS} < 1\cdot10^{-5}\mathrm{m^3/s\cdot m} \\ 1.0 + 15\cdot\left(\dfrac{-\log q_{SS} - 2}{3}\right)^3 & \text{for } q_{SS} < 1\cdot10^{-2}\ \mathrm{m^3/s\cdot m} \\ 1.0 & \text{for } q_{SS} \geq 1\cdot10^{-2}\ \mathrm{m^3/s\cdot m} \end{cases} \quad (3a)$$

Steep sloping rubble mound breakwaters (based on slope 1:1.4):

$$f_{scale\_nw} = \begin{cases} 6.0 & \text{for } q_{ss} < 1.10^{-4}\ \mathrm{m^3/s.m} \\ 1.0 + 5\ .\left(\dfrac{-\log q_{ss} - 2}{2}\right)^3 & \text{for } q_{ss} < 1.10^{-2}\ \mathrm{m^3/s.m} \\ 1.0 & \text{for } q_{ss} \geq 1.10^{-2}\ \mathrm{m^3/s.m} \end{cases} \quad (3b)$$

For slopes in between the tested slopes interpolation is possible.

Finally the prototype overtopping discharge to be expected can be calculated by multiplying the Froude upscaled small scale value qSS with the selected scale factor.

4. CONCLUSIONS

A generic prediction method for wave overtopping at coastal structures has been developed within CLASH. The background and application of this method has been briefly described in this paper. Furthermore the scaling procedure developed within CLASH has been explained. The exact figures in the formulae calculating scale factors are still the subject of ongoing research, but the main trends give indications on the magnitude of the scaling factor.

Acknowledgements

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